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Field assessment of Lake Erie dredged sediment for specialty crops cultivation

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Abstract

Annually, approximately 1.5 million tonnes of sediment are dredged from federal navigational channels in Lake Erie. Recognizing the potential influence of Lake sediments on soil compaction, structure, water retention capacity, and aeration, this research assessed the agronomic performance of selected specialty crops under varying sediment ratios in an open-field production system. The experimental design involved three sediment application rates: 0 tonne (100% farm soil), 0.7 tonne (90% farm soil and 10% sediment), and 7 tonnes per bed (100% sediment). Lettuces (*Lactuca sativa* L.) were harvested 35 days after planting, with assessments including fresh and dry weights of leaves root biomass and root length measurements. Radishes (*Raphanus sativus* L.) were evaluated for root length, leaf fresh weight, root fresh weight, and diameter. Tomatoes (*Solanum lycopersicum* L.) plants were monitored for plant height and stem diameter. Fruit harvest occurred at days 70 and 75 post-transplant. Metrics such as total number of marketable fruits, total fruit weight, number of US grade-1 fruits, and polar and equatorial diameters were recorded. The results revealed significant positive effects of the 7-tonne sediment treatment on lettuce, including increased dry leaf and root biomass, root lengths, and fresh weight. Similarly, radishes exhibited enhanced weight and length when grown in beds with 7 tonnes of sediment. Tomatoes from the 7-tonne sediment treatment displayed higher values in plant measurements and harvested fruits. Overall, the findings indicate that soils treated with Lake Erie sediment positively influence the development and production of lettuce, radishes, and tomatoes compared to untreated soils.

1 | INTRODUCTION

Since 1960, governmental agencies have been concerned about water quality issues in the Great Lakes. One of the most alarming cases was Lake Erie, which the Environmental Protection Agency declared to be "dying" in 2011. The Lake Erie was plagued by a range of problems, from excessive

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Abbreviations: DAT, days after transplant; ED, equatorial diameter; LDW, leaf dry weight; LFW, leaf fresh weight; MF, marketable fruits; PD, polar diameter; RDW, root dry weight; RFW, root fresh weight; RL, root length; TW, total weight.

nutrient runoff to harmful algae blooms, threatening the Lake's Erie ecosystem and posing a risk to public health (US EPA, 2015). The problem has persisted over the years, with farmland erosion being a major contributor. Eroded sediments tend to flow within the Maumee River Watershed and are brought to Lake Erie during spring storms, further exacerbating the water quality problem. As a result, every year, approximately 1.5 million tonnes of sediment are dredged from the federal navigation channels in the Port of Toledo. Dredging is critical to the city's economic growth, as the port supports 7000 jobs and $669 million in economic activity annually (Fleetwood et al., 2022). Additionally, keeping the water clean is of utmost importance as Lake Erie is the source of drinking water for 11 million residents in the US Midwest (French et al., 2011).

Traditionally, dredged material was allocated by either disposing of it in Lake Erie's open waters or depositing it in man-made confined facilities. However, research has demonstrated that disposal of sediments in open waters can cause an increase in nutrient concentration, which decreases oxygen levels and causes death to thousands of fish (Liu et al., 2019; Moog et al., 2018). Consequently, in July 2020, the Ohio State Senate approved a bill that restrains the disposal of dredged sediment in open waters. All the dredged material must be disposed into confined areas, which also implies environmental and economic challenges (Liu & Coffman, 2016).

Identifying feasible alternatives for using the dredged sediment is critical for Lake Erie's water health and the surrounding population. One potential benefit of using the dredged sediment is to apply it as a farm soil amendment (Daniel et al., 2007). Soil amendment is a material used to improve the physical, chemical, and biological characteristics of soils with the main goal of improving roots and crop development (Garbowski et al., 2023). Traditional agricultural practices such as overgrazing, monoculture, excessive use of chemical fertilizers and pesticides, improper tillage, and inadequate water management have accelerated soil degradation in agricultural regions (Montgomery, 2007). Soil degradation reduces soil fertility by removing organic matter (OM) and nutrients (Pimentel, 2006), and without any regenerative action of fertility restoration, crops develop poorly (Lal, 2004; Tilman et al., 2002).

The literature in place suggests that the addition of lake sediment to soils increases the content of soil organic matter (SOM), some essential nutrients, and pH while decreasing bulk density (Brigham et al., 2021; Daniel et al., 2007; Darmody & Marlin, 2002). Researchers have also found that dredged sediments can increase soil cation exchange capacity (CEC) and water retention capacity (Develioglu & Pulat, 2017). Agronomic trial studies indicate that tomato and pepper plants cultivated in Lake Peoria sediment exhibited a greater dry weight in comparison to those grown in untreated farm soil. This resulted in an overall improvement in their development (Ebbs, 2006). Likewise, a study showcased that incorporating Illinois River sediment into an open-field experiment elevated the levels of boron (B), zinc (Zn), copper (Cu), and molybdenum (Mo) in corn plants. This enrichment in essential elements is conducive to the enhanced development of the crops (Darmody & Marlin, 2002). A recent study conducted by Brigham et al. (2021) investigated the impact of Lake Erie sediment on soybean growth under controlled environmental conditions. Their findings indicate that soybean plants grown with higher ratios of dredged sediment exhibit increased total biomass and yield compared to plants treated with low ratios of dredged sediment. These results suggest the potential benefits of incorporating Lake Erie sediment in agricultural practices as a farm soil amendment.

Considering the inherent challenges associated with Lake Erie sediment accumulation and the promising implications for soil properties and plant production, this study aims to further explore and address the benefits of using Lake Erie sediments in specialty crop production. Despite emerging positive effects of dredged sediments on crop production, no research has evaluated the benefits of growing specialty crops in open-field conditions using Lake Erie sediments. This study objectives are to evaluate (i) the vegetative development, (ii) root growth, and (iii) edible tissue production of radish, lettuce, and tomatoes grown under three ratios of Lake Erie sediment in an open-field production system. We hypothesize that dredged sediment will improve the total above and below biomass of the crops and that the edible tissue will have a higher development compared to plants grown on treatments with no addition of sediments.

Core Ideas

- This study examines Lake Erie sediment's effect on lettuce, radish, and tomato growth.
- The research presents novel findings showing positive crop responses, which can guide the sustainable use of sediment in agriculture.
- Applying 7 tonnes of sediment significantly increases biomass, root length, and fruit yield in the studied crops.
- Lake Erie sediment positively influences the development of lettuce, radish, and tomato plants.
- The results of this study provide insights into sustainable soil use and can guide improved agricultural practices.

2 | MATERIALS AND METHODS

2.1 | Field set up

The dredged sediment utilized in the experiment was obtained from the Great Lakes Dredged Material Center for Innovation located in Toledo, OH. The sediment was dry after being dewatered for 2 years in an open deposit equipped with drainage tiles. It was not processed in any particular way other than manual fragmentation and homogenization using a conventional rake.

The experiment was conducted in a homogeneous open field plot measuring 60 by 24 m (1440 m^2). In eight previous growing seasons, the field was dedicated to a no-tillage corn and soybean rotation system, with soybean being the crop cultivated in the immediately preceding season. The purpose of the study was to evaluate the growth and agronomic performance of three different crops: (i) Outredgeous Romaine lettuce (*Lactuca sativa* L.), (ii) Shunkyo Semi-Long radish (*Raphanus sativus*), and (iii) Marglobe tomato (*Solanum lycopersicum*). The crops were grown using three different ratios of Lake Erie sediment. The ratios (treatments) included 100% sediment, a mixture of 10% sediment and 90% farm soil, and 100% farm soil.

Our experiment employed a randomized complete block design, consisting of three blocks. Within each block, there were three raised beds, one for each treatment. Each raised bed was divided into three plots, with each plot containing five plants of the evaluated crops: tomatoes, radishes, and lettuce. Therefore, each block consisted of nine experimental units, resulting in a total of 27 experimental units (Figure 1). The plots were randomly assigned throughout the length of the bed to minimize any potential effects of variation in soil conditions. The raised beds are common in horticulture and involve creating elevated soil to improve drainage and increase soil aeration, promoting root health and development. Using a tractor with an adjustable disc bedder, all raised beds were constructed that were 24 m long, 1 m wide, and 0.3 m high.

Three days before raising the beds, the sediment material was applied in the areas where the beds were later established. In the sediment treatment (100% sediment), 7 tonnes of sediment material were spread per bed. In the mixture treatment (10% sediment–90% farm soil), 0.7 tonne of sediment were applied per bed. We determine the mixture treatment ratio based on recommendations from Brigham et al. (2021). The amount of sediment was determined by calculating the volume of each raised bed based on their dimensions. No sediment was used in the 100% farm soil treatment, which is classified as a Hoytville clay loam with 0%–1% slopes (HoA) (USDA, Natural Resources Conservation Service, 2024). The farm soil treatment was established using soil from the field. No farm soil was transported in.

To ensure proper mixing of the treatments in each bed, including the beds without sediment, a rototiller was employed. Following the mechanical operation, the beds were raised and covered with 1.0 mm black plastic mulch. However, since the radishes were the only crop directly planted using seeds, we intentionally removed the plastic mulch from the radish plots and replaced it with straw mulch.

Once the beds were raised, three subsamples of soil were randomly collected at a depth of 30 cm from all beds using a push probe. We then mixed the subsamples to obtain aggregated samples for analysis. The samples were placed in bags and dispatched for chemical analysis. This analysis included determining levels of calcium (Ca), phosphorus (P), potassium (K), and magnesium (Mg) using the Mehlich 3 (M3) extractant. Additionally, pH, CEC, and SOM were determined as part of the chemical analysis process. We also submitted the samples for physical analysis of treatment particle sizes and to categorize the texture of the resulting blends. Moreover, we collected samples for bulk density measurements. Three samples for each treatment were collected after harvesting the crops, using a cylinder at a depth of 15 cm. The samples were then oven-dried at 105˚C until their weight remained constant. This process ensures that all moisture content is removed, allowing for accurate bulk density calculations. We proceed with standard calculation to determine the bulk density measurements.

Afterward, we transplanted lettuce seedlings that were 30 days old into their respective plots in the raised beds. Tomato seedlings, aged 35 days, were purchased from a local nursery and transplanted in the field. As for the radishes, their seeds were directly sown into the plots. To protect the radish seeds from abiotic (e.g., temperature fluctuations, moisture loss, and soil erosion) and biotic (e.g., weed competition and pest damage) factors, we covered the radish plots with straw mulch immediately after sowing. After 4 days, the mulch was removed from all radish plots. The crops were carefully arranged in a spatial manner, with a spacing of 25 cm between plants for lettuces and radishes, and 45 cm between tomato plants. Throughout the growing season, plants were watered manually using a hose, ensuring that the water was applied directly to the soil and not the foliage. Irrigation was conducted every other day, with adjustments made to skip days that experienced rainfall. No synthetic fertilizers or pesticides were applied. We followed standard agricultural practices for all crops. For radishes, weeding and cultivation were necessary. The areas between beds were managed using conventional hand tools like rakes, as well as power tools such as lawn mowers and garden trimmers. For tomatoes, staking was required.

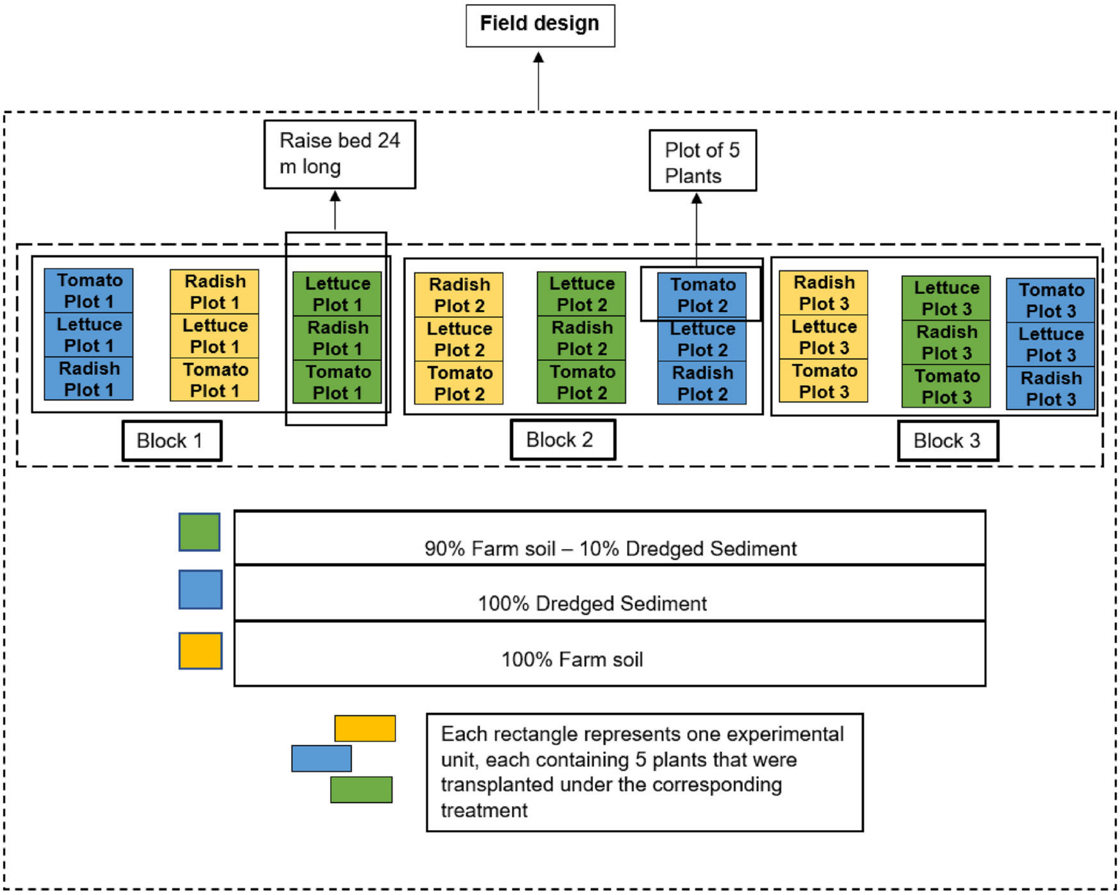

FIGURE 1 Layout of the experimental design.

2.2 | Study site

2.2.1 | Weather conditions

This study was carried out at the Agricultural Incubator Foundation, located in Bowling Green, OH (41˚27′29.8″ N 83˚39′54.0″ W), from June to September 2022. Ohio has a humid continental climate, as classified by the Köppen climate system. Throughout the experiment, the weather conditions varied, with the maximum temperature reaching 34˚C in June and the lowest temperature recorded at 5˚C in September. August experienced the highest precipitation (166 mm) and September experienced the lowest precipitation (27 mm; Table 1) (National Weather Service; Station number OH-WD-12).

TABLE 1 Monthly maximum, minimum, and average temperature, and cumulative monthly precipitation at the Agricultural Incubator Foundation 2022.

Temperature (˚C)	June	July	August	September
Max	34	35	33	30
Min	7	15	12	5
Average	21	24	23	18
Precipitation (mm)	107	151	166	94

Abbreviations: Max, maximum; Min, minimum.

Source: National Weather Service. Station number: OH-WD-12. Station name: Bowling Green 2.7 NW.

2.3 | Data collection

2.3.1 | Lettuce

After 35 days from transplanting, lettuce plants were harvested by excavating a hole around the plant stem, measuring 30 cm in length, 30 cm in width, and 30 cm in depth to retain the belowground biomass. Afterward, harvested plants were transported to the lab for analysis. Next, the lettuces were trimmed at the point where the stem and roots intersect using scissors. We washed and cleaned both the aboveground and belowground biomass to remove all substrate particles. The fresh weight of the aboveground and belowground biomass was measured separately using a digital scale with an accuracy of 0.01 g. To determine root length (RL), we measured the roots of each plant using a ruler. Following this, we segregated the root and foliage sections and deposited them into distinct paper bags. Subsequently, a mechanical VWR oven model Gr Con 2.3CF was used to dry the contents at 60˚C until the bags attained a consistent weight.

2.3.2 | Radishes

After a period of 35 days from sowing, the radishes were harvested and washed to remove all substrate particles. We kept the leaves of the radishes intact and transported the plants to the lab for analysis. To determine the fresh weight of the leaves and root sections, a digital scale with an accuracy of 0.01 g was used. Additionally, the length of the radishes was measured using a ruler, starting from the root crown and extending to the tip, excluding any etiolated portions. To assess diameter, we used a caliper to measure the crown, middle, and near tip of the radishes. These three measurements were then averaged to obtain a single data point.

2.3.3 | Tomatoes

We measured the plant height and stem diameter at specific time points 14, 28, 42, 56, 63, and 70 days after transplant (DAT). Plant height was determined by measuring the distance from the ground to the highest point of the main apex for all five plants within each plot. The stem diameter was measured at ground level using a caliper. We harvested the tomato fruits at two different time points: on 70 and 75 DAT, when the fruits displayed a pink color with over 30% red coverage but <60%. To reduce human visual error, we followed the color classification requirements outlined in the United States standards for grades of fresh. Subsequently, the total weight (TW) of the fruits per plot for each harvest was measured. We counted the fruits and weighted them using a digital scale with an accuracy of 0.01 g. Only fruits without cracks, damage from insects, diseases, and wildlife (USDA, 1991) were considered for determining the marketable fruit count. Furthermore, after each harvest, we selected five US grade-1 fruits per plot, and we measured both the polar and equatorial diameters (EDs). To ensure consistency, the same fruit used to measure the polar diameter (PD) was utilized to measure the ED (Meseret et al., 2012). Once all the necessary data were collected, measurements from both harvests were averaged and treated as a single harvest for statistical analysis.

2.4 | Statistical analysis

We analyzed data using the PROC MIXED procedures of the program "Statistical Analysis System," SAS version 9.4. We used the Shapiro–Wilk test ($p = 0.05$) to check for the normality of the data. The normality of the data were met, and the data were analyzed through an analysis of variance and mean separations of the Tukey test with a level of significance of $p \leq 0.05$.

To analyze the repeated measurements in the tomato crops, we treated treatment (ratios of Lake Erie sediment) and time points DAT as fixed effects to evaluate their impact on tomato plant height and stem diameter. The interaction between treatment and time was also included as a fixed effect to understand how the treatment effects evolved over time. Block (repetition) and plots within blocks were considered random effects to account for variability among the blocks and within-block variability.

3 | RESULTS

3.1 | Soil chemical analyses

The sediment treatment exhibited a higher pH compared to the farm-soil treatment, but no statistical difference compared to the mixture treatment. For CEC and Ca, the sediment treatment had higher and statistically significant measures compared to both the farm soil and mixture treatments. For P, the sediment treatment was statistically higher compared to the farm-soil treatment, with no statistical difference compared to the mixture treatment. The mixture treatment showed no statistical difference compared to the farm-soil treatment for P. As for K, Mg, and SOM, there were no statistical differences among any of the treatments (Table 2).

3.1.1 | Soil physical analyses

The particle analysis indicated that all three treatments were classified as "clay." However, the sediment treatment had a lower clay percentage and a higher silt percentage in comparison to the mixture and farm-soil treatments. The farm-soil treatment exhibited a higher clay percentage compared to both the sediment and mixture treatments. In terms of sand percentage, the mixture treatment had a higher sand content compared to the sediment and farm-soil treatments. For bulk density, the sediment treatment had the lowest value among the three treatments, whereas the farm-soil treatment had the highest bulk density value (Table 3).

3.2 | Crop measurements

3.2.1 | Radish

The radishes cultivated in the sediment treatment exhibited statistically greater measurements of RL, root fresh weight (RFW), and leaf fresh weight (LFW) compared to those grown in the mixture and farm-soil treatment. Although there

TABLE 2 Average values and standard deviations in parenthesis for the chemical characterization of the treatment blends.

Treatment	pH	CEC (meq/100 g)	Ca (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Mg (mg kg^{-1})	SOM (%)
Farm soil	7.0b (0.2)	20.1b (0.5)	2988b (169.7)	66b (8.6)	245a (75.8)	500a (13.1)	4.7a (0.9)
Mixture	7.5a (0.1)	26.4b (5.8)	4364b (173.0)	69ab (7.5)	230a (74.3)	476a (19.1)	4.2a (0.2)
Sediment	7.9a (0.1)	37.8a (1.7)	6692a (353.4)	89a (8.0)	186a (11.0)	459a (20.8)	4.2a (0.3)

Note: Means followed by distinct letters in the column are statistically different by the Tukey test at a 5% probability level. Meq/100 g: Milliequivalents per 100 grams. Mg Kg^{-1}: Milligrams per kilogram. *Source*: A&L Great Lakes Laboratories, Inc. Farm soil: raised bed made of 100% farm soil, Mixture: raised bed with 0.7 tonne of Lake Erie dredged sediment mixed with farm soil, sediment: raised bed with 7 tonnes of Lake Erie dredged sediment.

Abbreviations: CEC, cation exchange capacity; SOM, soil organic matter.

TABLE 3 Results from the physical characterization analysis of the treatment blends.

Treatment	Clay (%)	Sand (%)	Silt (%)	Bulk density (g/cm^3)	Classification
Farm soil	46	27	27	1.09	Clay
Mixture	43	30	27	1.07	Clay
Sediment	41	23	36	0.96	Clay

Source: Waypoint analytical. Farm soil: raised bed made of 100% farm soil, mixture: raised bed with 0.7 tonne of Lake Erie dredged sediment mixed with farm soil, sediment: raised bed with 7 tonnes of Lake Erie dredged sediment.

TABLE 4 Statistical significance and standard deviation in parenthesis of the main treatments in the agronomical evaluation of radish cultivar Shunkyo semi-long.

Treatment	Root length (cm)	Root fresh weight (g)	Leaf fresh weight (g)	Diameter (mm)
Farm soil	6.41b (1.69)	18.57b (10.76)	16.98b (8.33)	17.50a (4.10)
Mixture	6.70b (2.19)	18.78b (13.59)	20.14b (7.03)	22.52a (13.20)
Sediment	13.67a (2.69)	68.72a (24.54)	43.52a (9.50)	25.24a (3.74)

Note: Values are the means of three replicates. Means followed by distinct letters in the column are statistically different by the Tukey test at a 5% probability level. Farm soil: raised bed made of 100% farm soil, mixture: raised bed with 0.7 tonne of Lake Erie dredged sediment mixed with farm soil, Sediment: raised bed with 7 tonnes of Lake Erie dredged sediment.

was no statistical variation in the average diameter of radishes across treatments, the Sediment treatment displayed radishes with the highest average diameter (Table 4).

3.2.2 | Lettuce

The lettuces cultivated in the sediment treatment were statistically higher for leaf dry weight (LDW) and root dry weight (RDW) in comparison to the lettuces grown in the mixture and farm-soil treatment. Lettuces from the farm-soil treatment had higher and statistically different measures for LDW and RDW compared to the Mixture treatment. There were no statistical differences in the LFW values among all the treatments for the lettuces. The RL measurement of the lettuces grown in the sediment treatment was higher compared to farm soil but had no statistical difference compared to the mixture treatment. The RL of the mixture treatment had no statistical difference compared to the farm-soil treatment. Regarding RFW, the lettuces grown in the sediment had higher weight compared to the plants grown in the mixture treatment, but there was no statistical difference versus farm-soil treatment (Table 5).

3.2.3 | Tomato

The plants cultivated in the sediment treatment had higher means per plot of marketable fruits (MF), TW, and US grade-1 fruits compared to those grown in the mixture and farm-soil treatments. Conversely, no statistical variations were observed in the MF, TW, and US grade-1 between the fruits harvested from the farm-soil and mixture treatments. The results also showed that the ED and PD of the fruits harvested from the sediment treatment were higher compared to those harvested from the mixture and farm-soil treatments. No statistical difference was found between the fruit's ED and PD from the mixture and farm-soil treatments (Table 6).

The growth patterns of tomato plants in terms of height and diameter aligned with the observed trends in fruit yield and conformation. During the initial two measurement times, no

TABLE 5 Statistical significance and standard deviation in parenthesis of the main treatments in the agronomical evaluation of lettuce cultivar Romain.

Treatment	Leaf dry weight (g)	Root dry weight (g)	Leaf fresh weight (g)	Root length (cm)	Root fresh weight (g)
Farm soil	18.51b (1.43)	2.26b (6.57)	55.02a (22.15)	6.4b (2.20)	4.48ab (1.41)
Mixture	10.11c (0.55)	1.31c (1.87)	58.21a (36.35)	7.3ab (2.40)	3.90b (2.48)
Sediment	26.54a (0.50)	3.00a (15.77)	77.33a (55.91)	9.0a (3.20)	5.82a (2.78)

Note: Values are the means of three replicates. Means followed by distinct letters in the column are statistically different by the Tukey test at a 5% probability level. Farm soil: raised bed made of 100% farm soil, mixture: raised bed with 0.7 tonne of Lake Erie dredged sediment mixed with farm soil, sediment: raised bed with 7 tonnes of Lake Erie dredged sediment.

TABLE 6 Statistical significance and standard deviation in parenthesis of the main treatments in the evaluation of tomato fruit cultivar Marglobe harvested after 70 and 75 days of seedlings transplant.

Treatment	Marketable fruits (n)	Total weight (g)	US grade-1 (n)	Equatorial diameter (mm)	Polar diameter (mm)
Farm soil	25.66b (4.24)	1861.67b (888.00)	15.33b (5)	53.92b (8.01)	50.39b (4.81)
Mixture	27.67b (2.78)	1957.33b (2294.65)	14.33b (14)	56.12b (8.96)	49.20b (4.52)
Sediment	68.00a (7.43)	6055.67a (733.73)	37.66a (6)	66.59a (6.43)	56.30a (4.29)

Note: Values are the means of three replicates. Means followed by distinct letters in the column are statistically different by the Tukey test at a 5% probability level. Farm soil: raised bed made of 100% farm soil, mixture: raised bed with 0.7 tonne of Lake Erie dredged sediment mixed with farm soil, sediment: raised bed with 7 tonnes of Lake Erie dredged sediment.

TABLE 7 Statistical significance and standard deviation in parenthesis of the main treatments in the diameter and height of tomato plant cultivar Marglobe during 70 days after transplant (DAT).

	Treatment	DAT 14	DAT 28	DAT 35	DAT 42	DAT 49	DAT 70
Stem diameter (mm)	Farm soil	7.35a (1.42)	8.77a (1.48)	9.38b (2.00)	11.06b (1.75)	10.36b (2.12)	12.40b (2.38)
	Mixture	7.46a (1.79)	8.60a (0.98)	9.59b (1.19)	11.26b (1.31)	11.18ab (2.69)	37.51a (13.23)
	Sediment	8.47a (1.47)	10.12a (1.43)	11.57a (1.74)	13.61a (1.47)	13.39a (2.19)	42.02a (8.85)
Height (cm)	Farm soil	27.07a (5.65)	31.60a (8.23)	38.67a (9.34)	45.73b (8.52)	55.33a (6.76)	59.80a (7.50)
	Mixture	26.47a (9.16)	32.80a (9.95)	41.27a (10.15)	51.53b (11.99)	55.73a (13.10)	61.17a (12.23)
	Sediment	27.40a (9.14)	33.89a (6.22)	43.87a (8.42)	55.07a (8.53)	64.47a (9.47)	69.13a (8.5)

Note: Values are the means of three replicates. Means followed by distinct letters in the column are statistically different by the Tukey test at a 5% probability level. Farm soil: raised bed made of 100% farm soil, mixture: raised bed with 0.7 tonne of Lake Erie dredged sediment mixed with farm soil, sediment: raised bed with 7 tonnes of Lake Erie dredged sediment.

statistical differences were found in height and stem diameter. However, on DAT 35 and 42, tomato plants cultivated in the sediment treatment started exhibiting a higher stem diameter compared to those grown in the mixture and farm-soil treatments. On DAT 49 and 70, the plants in the sediment treatment maintained a higher stem diameter, but no statistical difference was observed when comparing them to plants from the mixture treatment. It is worth noting that both the sediment and mixture treatments resulted in higher stem diameter means compared to the plants grown in the farm-soil treatment (Table 7).

In terms of plant height, a statistical difference was observed only on DAT 42 among the treatments. The plants cultivated in the sediment treatment displayed a greater height compared to those from the farm-soil and mixture treatments. Despite the absence of statistical differences on DAT 14, 28, 35, 49, and 70, the plants grown in the sediment treatment consistently exhibited greater height compared to those from the mixture and farm-soil treatments. These findings indicate the potential positive influence of the Sediment treatment on plant height, promoting plant growth and development.

4 | DISCUSSION

We investigated the agronomical performance and edible tissue production of radish, lettuce, and tomato cultivated in varying ratios of Lake Erie dredged sediment within an open field raised beds production system. Our initial focus was on conducting chemical and physical characterization of the treatments. It is widely recognized that increased bulk density impede seed and transplant establishment as well as root development, ultimately resulting in decreased yield (Alvarez & Steinbach, 2009; Rasmussen, 1999; Sithole et al., 2016). In our experiment, we observed lower bulk density values in the sediment treatment compared to the mixture and farm-soil treatments (Table 3). The distribution and sizes of pores are often regarded as reliable indicators of soil physical conditions, with bulk density serving as a key determinant of soil porosity. Consequently, higher bulk density values correspond to lower porosity (Hao et al., 2008).

Plants cultivated in the sediment treatment potentially benefited from improved water movement within the soil, likely due to the higher porosity, which may have resulted in enhanced root development. Evaluation of radish plants revealed longer and heavier roots in the sediment treatment compared to the mixture and farm-soil treatments. Although we did not directly measure soil structure and aggregation, the observed differences in root development can plausibly be linked to these factors. Insufficient water movement, possibly stemming from poorer soil pore structure and aggregation, may have restricted the development of adventitious roots in the farm-soil and mixture treatments, causing reduced photosynthetic rates. This could explain the comparatively lower development observed in plants from these treatments. (Mngoma et al., 2022; Peterson et al., 1991).

Although soil porosity was not statistically evaluated in this study, it is plausible that the aggregation of sediment particles in the sediment treatment played a significant role in promoting plant development. According to Ontl et al. (2015), SOM is a reliable predictor of soil aggregation. While the OM percentage was statistically equal across all treatments (as reported in Table 2), previous studies using different treatments—including 100% Lake Erie sediments, a mixture of 90% Farm soil and 10% Lake Erie sediment, and 0% Lake Erie sediment—revealed a significantly higher concentration of total organic carbon in the sediment treatment compared to farm soil (Sequeira et al., forthcoming).

Additionally, research indicates that Lake Erie's sediment exhibits a remarkable water retention capacity, with 2.22 kg of sediment absorbing 598.74 mL of water, representing a 79% increase compared to a commercial substrate (Bhairappanavar et al., 2018). Improved soil aggregation and structure have been associated with enhanced soil water movement, water retention, nutrient cycling, root penetration, and crop yield (Bronick & Lal, 2005; Lal, 1991; Lupwayi et al., 2001; Munyanziza et al., 1997; Six et al., 2000).

Although we did not directly measure particle density to calculate porosity, the observed plant development in the sediment treatment suggests that superior water movement and distribution likely occurred, enabling better access to dissolved nutrients. This, in turn, may have contributed to the improved plant development observed in our study.

The chemical analysis indicated that all nutrients examined were present in the three treatments at levels considered desirable for tomato production, with the exception of K, which fell below the recommended levels for optimal plant development (Sainju et al., 2003). Nonetheless, tomato plants cultivated in the sediment treatment exhibited enhanced stem diameter, fruit yield, and fruit dimensions compared to plants grown in the mixture and farm-soil treatments. In a similar fashion, lettuce and radish displayed increased vegetative growth and root development when cultivated in the sediment treatment. Two prominent chemical characteristics exert significant influence on soil nutrient conditions, playing a crucial role in crop development and fruit production. First, pH is a primary factor affecting chemical and biochemical reactions, leading to availability and solubility of nutrients (Price, 2006). In our study, the pH measurement in the sediment treatment was 7.9, indicating an alkaline nature (Thomas, 1996). Even though high pH conditions typically result in decreased availability of P (Penn & Camberato, 2019), the elevated P content in the sediment treatment may have counterbalanced the availability limitation imposed by the alkaline pH. This can be inferred from the observation of tomato stem diameter, as previous research by Chatterjee and Dube (2004) demonstrated a direct influence of P content on the stem diameter of tomato plants. In our study, P levels in the sediment treatment were approximately 25% higher than those in the farm-soil treatment. Moreover, the availability of cations such as Mg, K, and Ca is not limited by alkaline pH, indicating comparable cation availability across all treatments (Sharpley, 1991).

However, pH also has a significant influence on CEC, impacting crop development. The CEC provides a valuable direction for soil fertility and nutrient retention capacity (Helling et al., 1964). In our study, the CEC in the sediment treatment was statistically higher compared to that of the farm-soil treatment. As soil pH increases, hydrogen ions decrease, causing negatively charged sites on soil particles, such as clay minerals and SOM, to become more negatively charged. This increase in charge enhances the CEC (Helling et al., 1964). Consequently, soil particles can attract and retain positively charged ions, including essential plant nutrients such as Ca, Mg, and K. These nutrients also promote a higher microbial community within the soil (Bulluck et al., 2002). Despite the lower levels of K and Mg in the sediment treatment in comparison to the farm-soil and mixture treatments, no statistical differences were observed among the three treatments. In contrast, the higher statistical values of CEC in the sediment treatment compared to the mixture and farm-soil treatments may have contributed to a greater reservoir of cations available to plants, potentially enhancing the absorption of K, Mg, and Ca. This, in turn, may have resulted in plants exhibiting greater root and leaf measurements, and fruit production compared to plants cultivated in the farm soil and mixture treatments. Additionally, the increased levels of P and Ca in the sediment may have contributed to improved soil aggregation, leading to enhanced plant development in the sediment treatment. Our results corroborate with Santos et al. (1997), in which the authors conclude that the precipitation of phosphates and carbonates plays a role in strengthening soil aggregation.

Although radishes and tomatoes exhibited a similar trend of improved agronomical development with higher sediment content, the same pattern was not observed in the parameters analyzed for lettuce. The dry weight of both the aboveground and belowground parts of the lettuce plants was found to be statistically higher in plants grown in the farm-soil treatment compared to the mixture treatment. This difference in performance could potentially be attributed to the higher K content in the farm-soil treatment compared to the mixture treatment. Previous studies have reported that lettuce plants grown in a medium with reduced K levels exhibited a lower capacity for CO_2 fixation and increased mesophyll resistance, ultimately leading to a reduced photosynthetic rate (Zhang et al., 2017). Based on this knowledge, we conjecture that the higher K content in the farm-soil treatment significantly contributed to the greater accumulation of dry matter in lettuces compared to the mixture treatment.

Regarding the influence of micronutrients, previous research suggests that lake sediments typically contain high levels of micronutrients due to the decomposition of OM, fluvial transport, biological activity, and the deposition of particles, making them a rich source of essential elements for plant growth. For instance, studies conducted by Ebbs (2006) demonstrated that tomatoes, broccoli, peppers, and carrots grown in Lake Peoria sediment consistently exhibited higher concentrations of Mo and Zn in their tissues compared to plants cultivated in farm soil. Although our experiment did not analyze micronutrient content in the treatments or plant tissues, we postulate that a similar enrichment of Zn and Mo may have positively influenced the development of crops, particularly tomatoes.

5 | CONCLUSIONS

The implementation of raised beds utilizing 100% Lake Erie sediment had a positive impact on the vegetative development, root growth, and edible tissue production of the three crops evaluated. We discuss that this positive effect can be attributed to several factors, including a higher CEC, nutrient availability, and lower bulk density. While our study provides robust findings, it is important to acknowledge certain limitations. One such limitation is the lack of nitrogen (N) concentration measures. Although our results clearly show that better crop development is directly related to the application of dredged material, the potential influence of N content remains an untested hypothesis in our study. Another notable limitation is the lack of replications over multiple growing seasons; our study was conducted within a single growing season. Based on our findings, we recommend further research in five key directions: (i) Extending the experiment over multiple years to provide valuable insights into the consistency and reliability of the observed effects. (ii) Including N concentration measures in the chemical analysis to address the potential influence of N content. (iii) Replicating the experiment using alternative commercial production systems would provide valuable insights into the feasibility and scalability of utilizing the dredged sediment in a broader spectrum of agricultural settings. (iv) Comparing the performance of crops grown in dredged sediments with crops grown using current commercial substrates would help assess the efficacy and potential advantages of dredged sediment-based cultivation. (v) Replicating the experiment while analyzing the micronutrient content, microbial activities, and bioaccumulation of heavy metals in the treatments would provide a more comprehensive understanding of the specific mechanisms underlying the observed crop development. The latter research front would also help elucidate the impact of Lake Erie sediments on soil health and food safety. These additional investigations would contribute to a more robust body of knowledge on the utilization of dredged sediment in agricultural practices.

AUTHOR CONTRIBUTIONS

Juan Pablo Sequeira: Data curation; formal analysis; investigation; methodology; resources; software; supervision; validation; visualization; writing—original draft; writing—review and editing. **Olusola Oyewumi**: Data curation; investigation. **Angélica Vázquez-Ortega**: Conceptualization; funding acquisition; project administration; resources; supervision; validation. **Guilherme Signorini**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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